Recurrent displacement of a forested earthflow and implications for forest management, East Coast Region, New Zealand

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Abstract Recurrent movement of a forested earthflow is documented over a 21-year period when two phases of activity were recorded, each separated by an interval of inactivity. Horizontal, vertical, and real-time surface displacements were measured. On both occasions the initiation of movement began in the headscarp region and activity propagated the 700-m length of this flow at times when soil moisture surplus exceeded the long-term winter average. Movement occurred as a series of "surges" followed by periods of deceleration. Our findings suggest that the critical failure threshold leading to the initiation of movement under closed-canopy forest is determined by the duration of antecedent soil moisture surplus and elevated pore water pressure, and is less a response to rainfall. Once initiated, however, surge-like movements are accelerated by heavy rainfall events and activity overlaps with periods of soil moisture deficit. There was no relationship between the initiation of earthflow activity and forest practices.

Key words earthflow; displacement rates; rainfall; soil moisture; forest harvesting

INTRODUCTION

Earthflows[1] are among the most common mass movement phenomena in nature and occur in many parts of the world's hilly and mountainous areas (Varnes, 1978; Keefer & Johnson, 1983; Iverson 1986; Bechini, 1993). In New Zealand's hill country areas, earthflows are an important form of mass movement (Campbell, 1966; McConchie, 1986; Zhang *et al*., 1991, 1993; Trotter, 1993; Crozier, 1996). Some two million hectares (27% of New Zealand's land area) are currently assessed as either having, or having a potential for, moderate to severe erosion resulting from earthflow activity (Eyles, 1983). Earthflows are most prevalent in the East Coast Region of the North Island (O'Byrne, 1967; Pearce, 1982; Marden *et al*., 1992) where one-third of the land mass is affected by earthflow activity (Smith, 1974).

Earthflows have been well characterised in terms of their association with geology. Crush zones associated with faulting are highly susceptible to earthflow activity (Pearce, 1982; Eyles, 1983), both in mudstones and in the normally more resistant argillite lithologies (O'Byrne, 1967). Earthflow failures occur where carbonate has been removed from calcareous mudstones as a result of acid-sulphate weathering of pyrite (Claridge, 1960; Pearce *et al*., 1981) and are also associated with weathering and loss of strength in calcareous mudstones that are free of pyrite and outside obvious crush zones (Trotter *et al*., 1991; Trotter 1993).

Earthflow activity has been correlated with intense rainstorms or moderate rainfall with wet antecedent conditions (McConchie, 1986; Iverson & Major, 1987; Bechini, 1993; Crozier, 1996), pore-water pressure response to rainfall (Keefer & Johnson, 1983; McConchie, 1986; Iverson & Major, 1987; Selby, 1993), and changing soil physical properties (Pearce *et al*., 1981; Pearce, 1982; Keefer & Johnson, 1983; Zhang *et al*., 1991, 1993; Trotter e*t al*., 1992; Trotter 1993). The majority of studies involving the measurement of earthflow displacement have been located in pastoral hill country (Pearce *et al*., 1981; Pearce, 1982; McConchie, 1986; Zhang *et al*., 1991, 1993; Trotter, 1993) with fewer studies focusing on forested earthflows (Blackwelder, 1912; Pyles *et al*., 1987). Comparative studies of earthflow behaviour between unforested and forested sites at the same location are rare (Zhang *et al*., 1993).

[1] The terms earthflow, earthflow deposit and earthflow complex are used in the senses defined by Keefer & Johnson (1983). An earthflow is a moving body of earth and water; once motion has ceased, the displaced material is an earthflow deposit. An earthflow complex is an assemblage of earthflow deposits and/or earthflows.

Land-use change, involving the planting of exotic forest on eroding hill country, is the primary soil conservation method used to control existing and mitigate against potential erosion (including earthflows) and has a proven effectiveness record in New Zealand (O'Loughlin & Zhang, 1986; Phillips *et al*., 1990; Marden & Rowan, 1993; Marden, 2004). Reforestation will continue to be used extensively to future-proof hill country considered vulnerable to earthflow erosion during climate change scenarios predicted for this region. It is important, therefore, to understand the implications of forest harvesting and its potential environmental impacts, both on- and off-site.

This study aimed to identify the factors controlling recurrent initiation and mobility of a forested earthflow. Our particular interest was to assess what effect, if any, harvesting might have had on the earthflow activity at this site, both at the time of harvesting and during a 15-year post-harvest/re-establishment period, and to assess the implications for future harvesting in similar earthflow-prone terrain.

FIELD SETTING AND DATA COLLECTION

Background

Wheturau earthflow is located in Mangatu Forest within the headwaters of the 2200-km^2 Waipaoa River basin (Fig. 1) in an area of hill country retired from pastoral farming and converted to exotic forest due to widespread and severe erosion. Established since 1961, Mangatu Forest covers 140 km^2. Before European settlement (about the turn of the 19th century), much of this hill country was covered in mixed podocarp–hardwood forest but was subsequently cleared (1860–1920) for pastoral farming. In response to increased runoff volumes and peak flows, a phase of stream downcutting was initiated, together with a noticeable increase in slide-flow failures (Pearce, 1982). The combined effects of loss of soil cohesion from tree roots, and increased soil moisture content as a result of reduced evaporative losses, may also have destabilised old earthflow/slide complexes that were marginally stable under a dense indigenous forest cover. The climate is warm temperate maritime, with a warm dry summer and autumn (November–March) and a cool wet winter and spring (April–October). Mean annual rainfall at the field site is 1350 mm (Pearce *et al*., 1987). Intense rainstorms result in flooding and often coincide with wet antecedent conditions, as in 1985, 1988 and 2005 (Phillips *et al*., 1990; Anon., 2006; Gisborne Herald, 2006a,b). The region is also prone to cyclonic storms, the most recent – Cyclone Bola in 1988 – caused widespread mass movement and flooding (Phillips *et al*., 1990).

Wheturau earthflow

Wheturau earthflow is visible in photographs taken in 1904 (shortly after the original forest cover was cleared), suggesting it was present under indigenous forest. The earliest available aerial photography (flown in 1939) shows that earthflow activity at this site was more widespread than at present. The main body of the earthflow (flow I) extends the full length (~700 m) of a zero-order drainage basin (21 ha) (Fig. 1(a)). The highest point of the basin is ~290 m a.s.l. The toe of the slope at river level is ~160 m a.s.l. Average surface inclination along the axis of the flow is 10–15° with some short and steep (20–25°) segments occurring throughout its uppermost two-thirds. For much of its length, flow I is confined within a linear depression 1–2 m below the level of adjacent stable ground and is bounded by prominent, near continuous, inward-sloping, steep (60°) and slickensided lateral shear surfaces. During previous phases of movement, material has overflowed these lateral shears to accumulate as levees averaging 1 m in height and preserved along much of the flow's length. In the upper part of the watershed, flow I divides into a north and a south branch each with a headscarp 3–4 m high. A small feeder flow (flow II) enters flow I in the lower part of the contributing basin. The toe-slope of flow I consists of a 90-m-wide accumulation of earthflow material piled into an irregularly shaped mound 4–6 m above the general level of adjacent stable terrain. The toe-slope has on several occasions displaced River Road and come to rest on aggradational alluvium in the Waipaoa River bed. The Waipaoa River is a rapidly aggrading, braided river system, and to our knowledge, bank erosion at the toe-slope of Wheturau earthflow has not occurred within historical times.

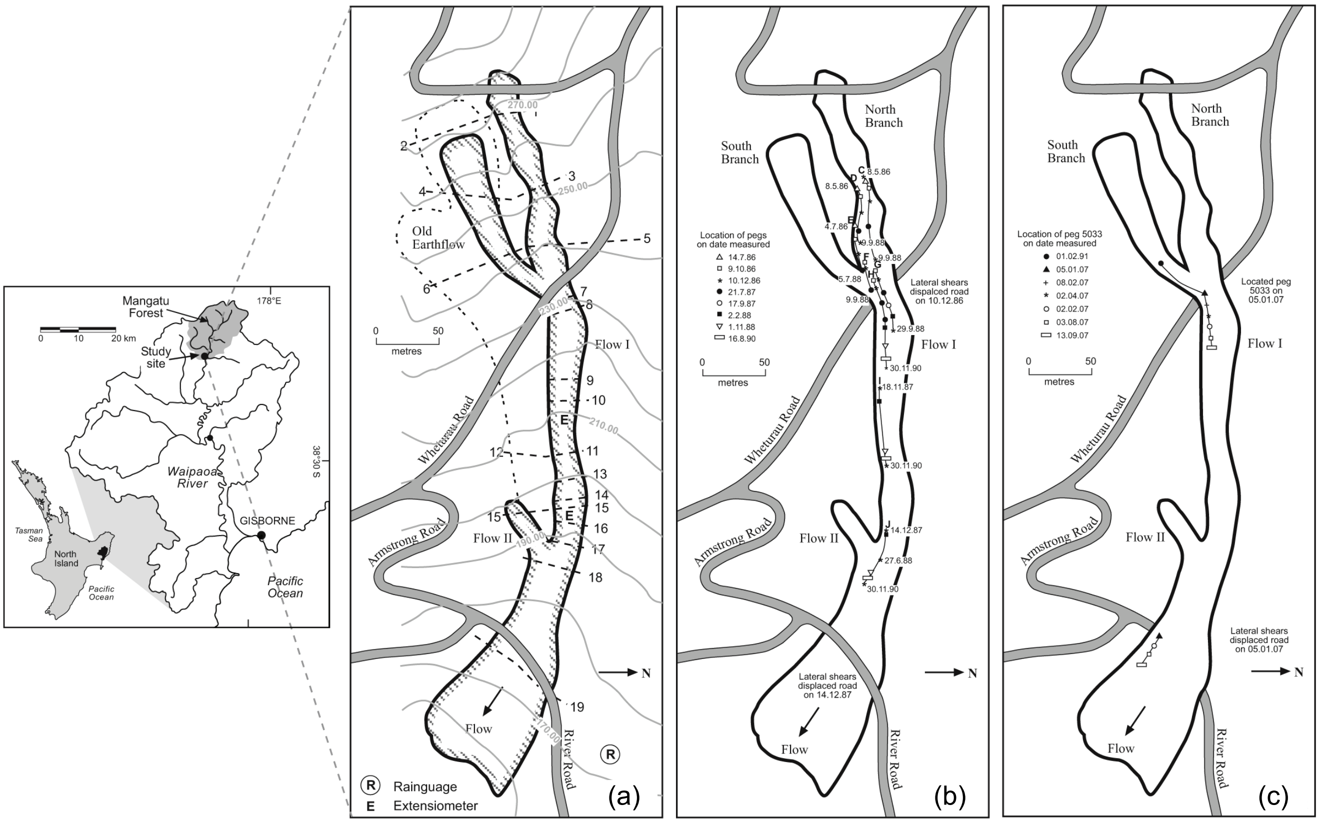

Fig. 1 Location map of study basin within Mangatu Forest. Inset A: Wheturau earthflow boundary (solid line), contours, old stable earthflow (dashed line), location of multi-peg transects (1–19), rain gauges (R), and extensiometers (E). Inset B: Surface displacement on Flow I during phase I (1986–1990) as indicated by the displacement of 'travelling-marker' pegs C, D, E, F, G, H, I and J. The first peg on each line marks the position and time of the first sign of separation along the lateral shear surface. Subsequent peg positions record displacements on the moving mass of earthflow material. Dates of movement initiation and termination are shown. Inset C: Surface displacements during movement phase II in 2007–2008.

In 1961, the dryer and more stable sites within the drainage basin were planted with radiata pine (*Pinus radiata*) while the lower-lying and poorly drained earthflow sites were planted with closely spaced (5 × 5m) poplar (*Populus*) and willow (*Salix*) species. At the time, these latter species were used extensively to stabilise actively moving earthflows, suggesting that this site may have been active prior to and/or at the time of planting. The understorey vegetation consists of sparse rank grass and native shrubby hardwoods.

In April 1986, and as part of a long-term soil moisture-monitoring programme, radiata pine was clearfelled from the northern side of the study basin and in March 1991 the trees from the remainder of the study basin were harvested. Poplars growing on the earthflow itself were largely destroyed during these harvest operations. Replanted in radiata pine in 1992, the trees were thinned in 2003 from 1000 to 400 stems per hectare.

Data sources

Previous research in the vicinity of the study site has focused on forest hydrology and erosion process studies, particularly on earthflows (Pearce *et al*., 1987; Marden *et al*., 1992). Rainfall data (1963 to present) were obtained from a nearby meteorological station (Fig. 1(a)). Neutron probe measurements to a depth of ~2 m from 13 access tubes located on stable ground adjacent to Wheturau earthflow, were used to establish relationships between soil-water storage patterns and earthflow movement (Pearce *et al*., 1987). These monthly data, collected since 1983, were also used to explore relationships between soil moisture levels and pore-water pressure (Marden *et al*., 1992). Although not represented here, this data is used extensively in the discussion on earthflow movement initiation. A survey network was installed to fix the position of relevant topographic features, instrumented sites, benchmarks and individual pegs along survey lines (transects) (Fig. 1).

Measurement of earthflow displacement

Surface displacement data were collected during two phases of movement activity (see Results). On both occasions, the first visible signs that movement was about to take place were the propagation of lateral shear surfaces, seemingly ahead of the moving body of the flow. Horizontal displacement was measured using "travelling markers". The first peg on each line (markers A to J, Fig. 1(b)) fixed the position and time of movement initiation and separation along the lateral shear surface. Subsequent peg positions record displacements on the moving mass of earthflow material. Each new location of a peg located on the mobile section of the earthflow was recorded, as it moved downslope, by placing a corresponding peg on stable ground opposite the travelling marker and recording the date. The distance and dates recorded on these pegs provided a record of surface displacement and displacement rates.

For the period 1986–1989 markers A to J (Fig. 1(b)) were used to track the first pulse of movement (phase I) as it propagated down the length of flow I. The study site was visited daily in the winter months when displacement rates were highest, and weekly during the summer months when activity slowed. Cumulative displacements recorded during this phase of activity are shown in Fig. 2. These markers were replaced at a later date with 19 multi-peg transects (Fig. 1(a)) with

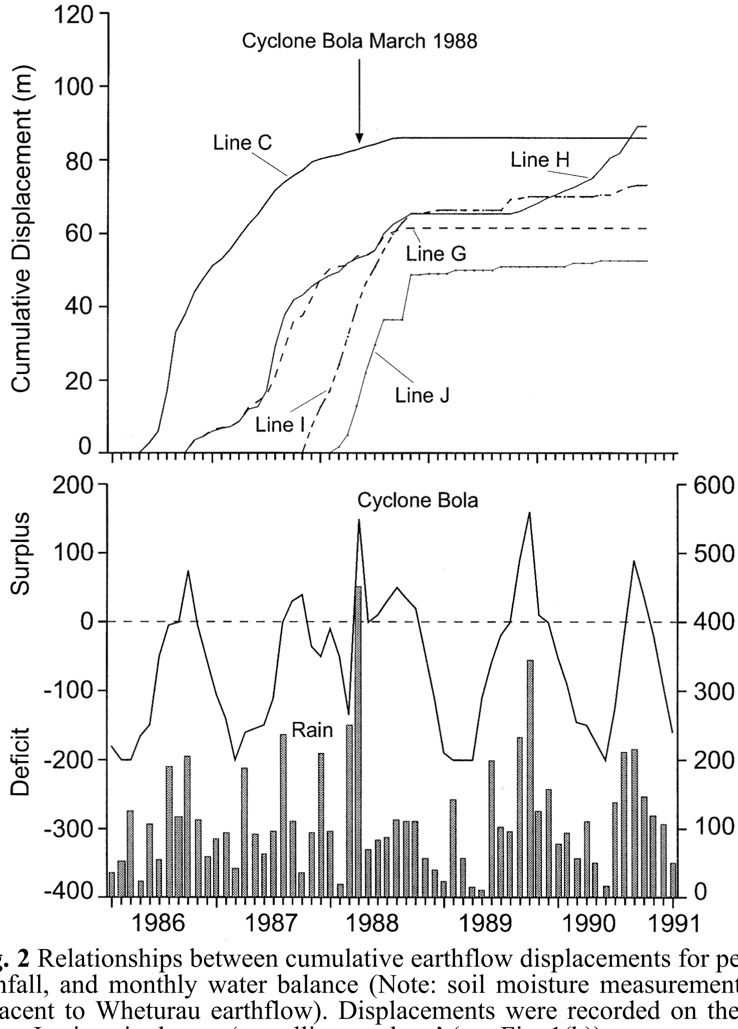

Fig. 2 Relationships between cumulative earthflow displacements for peg lines C, G, H, I, & J, monthly rainfall, and monthly water balance (Note: soil moisture measurements were made on stable ground adjacent to Wheturau earthflow). Displacements were recorded on the north branch of flow I during phase I using single-peg 'travelling markers' (see Fig. 1(b)).

the aim of recording differential rates and vectors of horizontal displacement together with elevation change across the width of flows I and II. These were recorded monthly using standard survey methods.

To improve the temporal resolution of earthflow displacement, continuous recording devices (extensiometers constructed from modified water level recorders) were also installed (Fig. 1(a)) and real-time displacements (1990–1991) recorded. During phase II, the initiation of newly formed lateral shears (January 2007) were found to extend between transects 7 and 19, but displacements were measured only at transects 7 and 19 (Fig. 1(a)). At transect 7, these were measured using the travelling marker method as previously described. The progressive displacement of River Road (transect 19) was recorded by measuring the offset distance of the "white line" marking the edge of the bitumen (Fig. 1(c)). Displacements were recorded monthly between January and December 2007. Surface displacement data from flows I and II recorded between 1986 and 2007 form the basis of material presented in this paper.

RESULTS

Displacement distances and rates

Between 1985 and 2007 there were two phases of earthflow activity, each separated by an interval of inactivity.

Phase I (1985–1992) The first indication of renewed earthflow activity at this site occurred in 1985 when a section of Wheturau Road, on its downhill side, collapsed at the point where it crossed the headwall scarp of the north branch of flow I (Fig. 1). This section of road was rebuilt but collapsed again in May 1986 by which time two parallel lateral scarps, 30 m apart, had formed and the section of flow I immediately below the headscarp had mobilised and been displaced 85 m downslope to transect 3 (Fig. 1(a) and (b)). There was no movement in the south branch at this time. By December 1986, earthflow displacements in the north branch had propagated to downslope of transect 7 (Fig. 1(b)), severing a 22-m-wide section of Wheturau Road at this point. By December 1987, River Road was closed at transect 19 when an 87-m-wide section of this road was displaced. Flow II became active during the winter of 1988 (before forest removal from this part of the study basin) but stalled when activity on flow I slowed. Earthflow activity during 1989–1990 was localised to the mid to lower section of flow I (between transects 11 and 18) with no disruption to either Wheturau or River roads. Displacements slowed considerably towards late 1990 and ceased during the summer of 1990/91. Minor displacement, initiated in 1988, continued on flow II at transect 15 during the winter months of 1991 and 1992, a period when no activity was recorded in either branch of flow I. During phase I, the opening of the lateral shears progressively down the 700-m-long flow occurred at an initial rate of 0.2 m day^{-1}, increasing to 0.7 m day^{-1} and culminated at 1.1 m day^{-1} to reach River Road 19 months after forming at the head of the flow. The greatest total displacement for any one section of flow I was recorded by travelling markers C (86 m) and H (89 m) (Figs 1(b) and 2). The maximum (0.9 m day^{-1}) and mean (0.15 m day^{-1}) daily displacement rates were highest during the first 12-month period (1986–1987), declining to 0.06 m day^{-1} within 2 years and averaging 0.04 m day^{-1} during the final 2-year period (1989–1990). Total displacements were substantially less (11–14 m) on flow II, with a maximum displacement rate of 0.1 m day^{-1} and averaging 0.07 m day^{-1}.

Phase II (2007) The second phase of earthflow activity occurred ~15 years after the watershed had been replanted (1992), and 4 years after thinning (2003). Movement began in the south branch (between transects 4 and 6) but was not detected on the main part of flow I until early 2007 by which time ~50 m of movement had already occurred (Fig. 1(c)). Total displacement during phase II at Wheturau Road (transect 7) was 41 m, averaging 0.2 m day^{-1}. In contrast, 29 m of displacement was recorded at River Road (transect 19) with initial displacement rates varying by an order of magnitude less than at transect 7 but increasing to between 0.5 m and 0.7 m day^{-1} just prior to the cessation of movement. The section of River Road displaced during this phase of movement was rebuilt in February 2008 and no further activity has been recorded since.

Displacements vectors and elevation change

Horizontal displacement was by slip at the lateral margins and by deformation along internal shear surfaces. Where the flow was narrow and of constant width, displacement occurred predominantly along the lateral shear surfaces with little initial internal deformation. Typically, displacement vectors of individual pegs paralleled the lateral margins and displacement amounts were equal across the width of the flow. As displacement quickened, movement near the centre of the flow exceeded that at the margins (Fig. 3) and occurred increasingly along internal shear surfaces within the moving mass. Generally, displacements along internal shears resulted in the redistribution of material within the flow so that some sections became temporarily depleted of material while other sections over-thickened. Where sections of the flow over-thickened, the elevation on the body of the flow often exceeded that of the adjacent stable ground and material overflowed to accumulate as a levee along the lateral margin of the flow. Invariably, material at over-thickened sections would be displaced along internal shear surfaces towards depleted (topographic lows) sections of the flow. As a consequence of material moving down the length of the flow, surface elevations at measured sections varied by up to 1 m, but averaged ~0.3 m (Fig. 4).

Displacement velocities

Real-time recordings of movement show that it occurs predominantly by surges during which a large cumulative displacement occurs over a short period of time separated by longer periods of deceleration (Fig. 5). For the measurement period shown in Fig. 5, surges accounted for ~80% of total displacement (50% of time) with ~20% of displacement occurring during the deceleration period. Surge displacement velocities averaged 0.4 m day^{-1} and during the deceleration period averaged 0.1 m day^{-1}. Over the 14-month period when the extensiometers functioned well (in 1990–1991), surges accounted for 62% of total displacement of which 60% occurred during the seasonally wetter winter and 40% during the traditionally drier summer months. Displacement rates and surge velocities recorded at Wheturau earthflow are within the range recorded in the international (Keefer & Johnson, 1983) and New Zealand literature (Campbell, 1966; McConchie, 1986).

Displacement, soil moisture and forest activity relationships

Although both phases of earthflow movement were initiated during periods of soil moisture surplus, and the largest individual surges and total cumulative displacements coincided with such

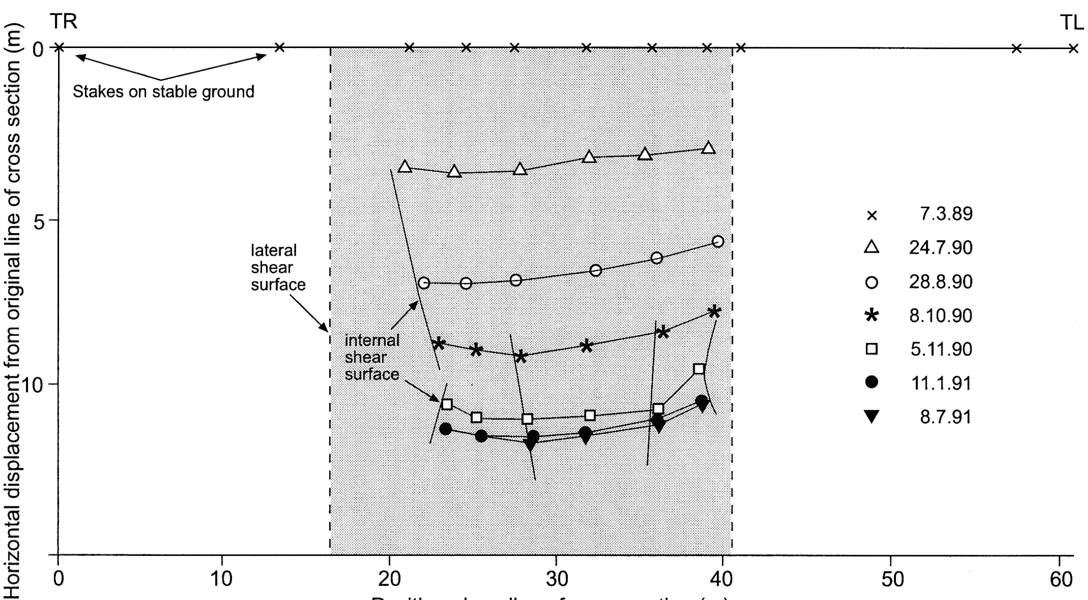

Fig. 3 Horizontal velocity plot (transect 11) showing a large component of displacement along lateral shears and smaller components of differential displacement along discrete internal shear surfaces.

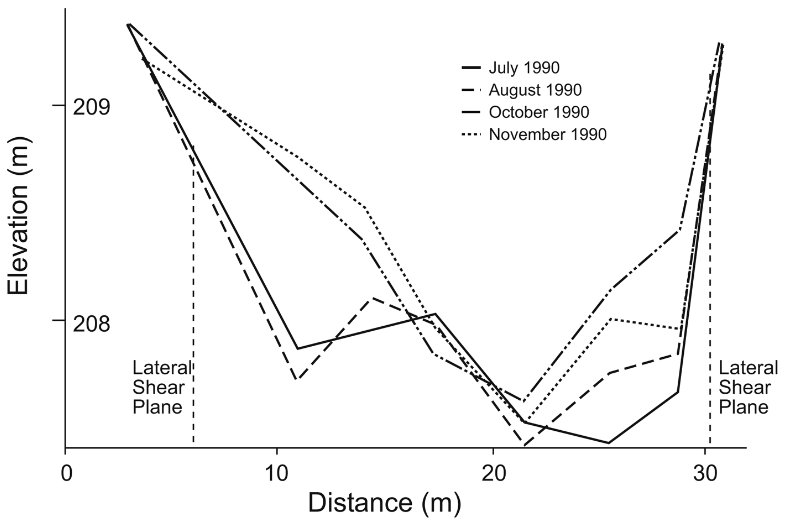

Fig. 4 Changes in vertical elevation across the width of the flow as material moves downslope and simultaneously from topographic highs to lows, with most displacement occurring along internal shear surfaces.

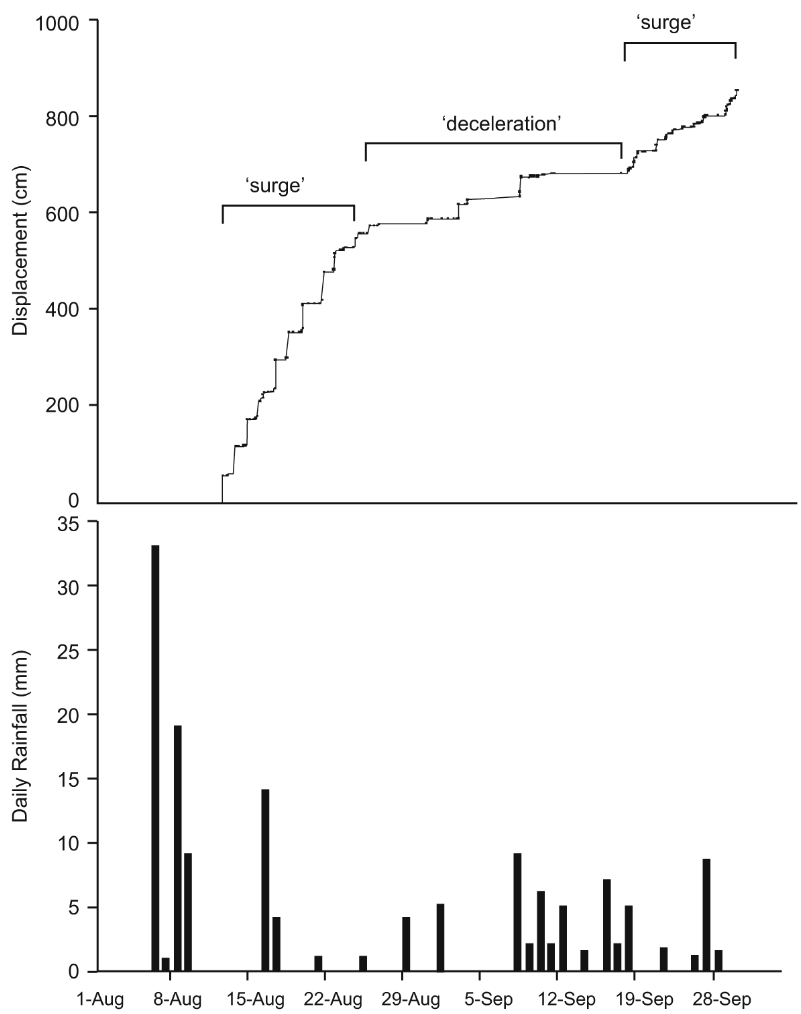

Fig. 5 Movement pattern recorded using a continuous-recording extensiometer and daily rainfall for the period 13 August–29 September 1991. Note the initiation of a short period of accelerated surge-like displacement after significant rainfall on 7 and 9 August, followed by a longer period of deceleration as rainfall tapered off.

conditions (Fig. 5), a significant proportion of activity was also associated with periods of soil moisture deficit (Fig. 2). There was no detectable earthflow activity during much of the post-harvest period once the cyclic pattern and magnitude of changes in water balance and in ground-water responses on stable ground had returned to pre-harvest levels, and these remained largely unaffected by thinning of the forest stand in 2003. It is considered likely that the initiation of the second phase of earthflow activity in the south branch (not detected on the main body of the flow until January 2007) coincided with the winter of 2006 when the water table rose within the normally dry neutron probe access tubes (no water balance data available) by up to 40 cm. These conditions prevailed for only 2–3 months. However, earthflow displacements persisted until the end of 2007 and were not related to forest activities.

DISCUSSION

Relationships between surface displacement, rainfall and soil-water storage

Both phases of earthflow movement mobilised after a period of inactivity with re-activation coinciding with the beginning of a long-term wet period. A number of reasons have been put forward to explain the mobilisation and activity of earthflows. Most relate to rainfall-induced mobilisation following wet antecedent conditions (McConchie, 1986; Iverson & Major, 1987; Bechini, 1993; Crozier, 1996) caused by high pore-water pressures contributing to reduced shear strength of the flow materials along shear surfaces (Keefer & Johnson, 1983; Reid & Iverson, 1992). To activate, a flow must become wet at depth, and this only occurs after periods of prolonged rainfall. Such conditions preceded earthflow initiation at Wheturau Road in 1985 and 1988 (phase I), and again in 2007 (phase II). During the 2006 winter, several independent accounts of localised, large-scale earthflow movement occurring within forested areas (Anon, 2006; Gisborne Herald, 2006a,b) have attributed this activity to above-average winter rainfall, in addition to which there had been an unusually high number of heavy rainfall events since a major flood in October 2005 (Gisborne Herald, 2006a,b).

The amount and distribution of rainfall throughout the year appear to be critical factors controlling the amount and timing of movement in earthflows. The movement patterns described as an initial surge followed by a period of smooth, gradual deceleration, typically occur during or shortly after rainstorms (Prior & Stephens 1972). These surges occur when the soil moisture content is at its maximum, and presumably when pore-water pressure briefly exceeds the threshold value required for initial mobilisation (Keefer & Johnson, 1983). Movement is greater when winter rainfall occurs early or when it is evenly distributed throughout this season. At Wheturau earthflow, the data indicated that an initial surge is likely to occur within days of a heavy rainfall event and gain sufficient momentum to continue moving during periods of lower rainfall before decelerating (Fig. 5). The short response-time between rainfall and movement is likely a reflection of the shallowness of the slope deposits and their clay-rich composition. Response times for materials on active parts of flows are likely to be quicker given that the material is severely disturbed and often reduced in thickness as a result of previous earthflow activity. In addition, earthflows invariably occupy topographically "low" drainage collection areas within which materials are likely to attain higher moisture contents earlier and remain in a wet state for longer. The duration of periods of soil moisture surplus, during which earthflow activity is likely to occur, will therefore be longer than that indicated by data collected from sites on stable ground. This may explain why earthflow activity in this region shows only a weak seasonal influence, and why significant amounts of earthflow movement can also occur during periods of apparent soil moisture deficit, as discussed below.

Earthflow displacement patterns correlate better with monthly water balance data than with rainfall. For four of the five years between 1986 and 1992, a greater proportion (60%, range 75–39%) of earthflow displacement occurred during periods of soil moisture surplus (~3 months) than during periods of soil moisture deficit. In 1988, on account of exceptionally heavy rainfall in March (Cyclone Bola), soil moisture surplus conditions persisted for longer (~7 months) during which 75% of the total displacement for that year occurred (Fig. 2). This relationship between earthflow displacement and soil moisture surplus, however, is not always consistent, as significant displacement can occur at times of soil moisture deficit as was the situation in 1987. In this instance there was a noticeable increase in displacement on lines G and H (Fig. 2) following two heavy rainfall events (March and July) each delivering in excess of 80 mm in one day and up to 200 mm in a week. About 60% of the total displacement for that year coincided with these events. Those sections of the flow actively moving at the time of these storms displayed a two- to three-fold increase in displacement while the non-active sections showed little to no response.

The response to Cyclone Bola (March 1988) was different again. There was a 2- to 3-week delay and variable response to this storm with some sections of the flow showing a minor increase in displacement (line C), while other sections showed a significant increase (lines G, H, I and J). The effect was greater on the already mobile sections of the flow than on the stationary sections (Fig. 2). These observations suggest the behavioural response of earthflows is influenced by the timing of intense rainfall events and by the activity of movement at the time of the event. If rainfall occurs at the start of the wet season, it is likely that desiccation cracks in the earthflow materials will still be open allowing rain and surface water to penetrate the flow material. Heavy-rainfall events during the wet season, when desiccation cracks are likely closed, will instead tend to increase runoff. We were unable to establish pore-water pressure levels required to initiate movement or at the time of cessation of earthflow movement at this site because no movement occurred at the time this data was collected (see Marden *et al*., 1992).

Influence of management activities on movement

The preceding analysis indicates some of the mechanisms likely to initiate and control the movement of Wheturau earthflow. Forest management activities can also influence movement in two ways. First, road and landing construction can alter surface drainage patterns, thereby altering the groundwater regime. Second, the evapotranspiration rate of a forest is temporally reduced after thinning and harvesting, increasing soil moisture and, possibly, groundwater levels.

Although the cause of the initial collapse at the head scarp of the north branch is unknown, it is clear that the addition of this material to the body of the then stable earthflow initiated the first phase of movement. Movement then increased when additional earth material was sidecast and surface runoff channelled onto the body of flow I during the reconstruction of Wheturau Road. In this instance, the top-loading of material onto the earthflow, whether natural or man-induced, triggered the first phase of movement and locally has prompted the adoption of best management practices for the construction of forestry roads in earthflow terrain. There is no evidence to suggest that Wheturau earthflow has been destabilised by the removal of the toe-slope, despite it protruding onto the wide, braided, riverbed of the rapidly aggrading Waipaoa River.

The influence that changes associated with harvesting could have on groundwater and ultimately earthflow movement, is a function of: (a) the groundwater regime, including the surface and subsurface watershed that contributes groundwater to the earthflow, (b) the portion of the watershed experiencing reduced evapotranspiration from harvesting, and (c) the time for evapo-transpiration to return to pre-harvest levels as the new stand develops.

The groundwater regime in this area of intensely sheared bedrock is likely to be complex. Groundwater springs issue from the headscarps of many earthflows, but the subsurface flowpaths, and hence the watershed area contributing groundwater to them, is unknown. Nonetheless, the response of the groundwater system to rainfall can be used as a basis for assessing the likely effect of clearcut harvesting on Wheturau earthflow.

Annual interception losses under mature *Pinus radiata* averaged about 35% of gross rainfall. When soil water was not limiting, transpiration rates ranged from 30 mm month^{-1} in winter to 90 mm month^{-1} in summer (Pearce *et al*., 1987). The measurement of soil-water content showed that these mature forests extract up to 200–250 mm of water from storage in the soil to meet their transpiration needs during summer. Soil-water storage is recharged slowly and often incompletely by winter rainfall, which is reduced in effectiveness because part is intercepted by the forest canopy.

Clearfelling of part of the watershed in April 1986, following a near-normal winter, showed a gradual wetting of the soil for 2–3 months until field capacity was reached. Water rose into some access tubes on the clearfelled areas, indicating a water table 1–2 m below the soil surface. By comparison, the maximum soil water content under forest was not reached until October 1986, by which time the clearfelled area had been near field capacity for 4 months (Jackson *et al.*, 1987).

During the 1986/87 summer period the soil profile under forest dried out thoroughly, but on the clearfelled areas drying was concentrated near the soil surface and little water was used below 0.5 m depth. However, once a complete weed cover had invaded the clearfelled site, the rates of transpiration calculated from the soil-water measurements were similar for the two sites (3.0–3.5 mm day^{-1}). Interception made rainfall less effective under forest, so that soil rewetting was delayed until late into the 1987 winter. Soil-moisture patterns for the sites clearfelled in April 1991 showed a similar trend. However, winter and autumn rainfalls were 25% down on previous years and soil moisture and water table levels did not reach previous levels. Wet soil conditions persisted for 1–2 months only before drying thoroughly during the 1991/92 summer. Since 1992, the cyclic pattern and magnitude of changes in water balance and in groundwater responses on stable ground within this replanted basin have returned to pre-harvest levels.

CONCLUSIONS

The recurrent surface displacement of Wheturau earthflow is a general response to periods of soil moisture surplus, heavy rainfall events and to the presence of cracks allowing rapid infiltration of rain water into the earthflow materials. Two movement phases were each preceded by prolonged periods of rainfall during which soil moisture levels exceeded the long-term winter average, indicating that earthflow initiation under closed-canopy forest is governed more by antecedent soil moisture levels and is less a response to periods of heavy intense rainfall. Nevertheless, once movement has been initiated, heavy rainfall can prolong movement into periods of soil moisture deficit. For earthflows, the critical failure thresholds leading to the initiation of movement are more likely to be determined by the duration of soil moisture surplus and elevated pore-water pressure than by vegetation cover. However, the significance of these factors is undoubtedly lessened by the presence of a forest cover resulting in fewer incidences of earthflow activity in forests than in pastoral hill country.

There was no relationship between the initiation of each phase of earthflow activity and the harvesting of the forested watershed surrounding this flow because: (a) the first phase of movement was initiated before the partial harvesting of the watershed surrounding Wheturau earthflow; (b) there was no response to the later harvesting of the remainder of this watershed or to thinning of the trees in 2003; (c) the cyclic pattern and magnitude of changes in water balance and in groundwater responses on stable ground within this replanted basin returned to pre-harvest levels within 2 years of harvesting; and (d) the second movement phase occurred under a closed-canopy forest 15 years after the watershed had been replanted.

Although it is inevitable that the harvesting of forests in earthflow terrain in the future will periodically coincide with prolonged periods of high soil moisture surplus and/or heavy rainfall events, it is considered unlikely that the practice of harvesting in itself will initiate new or renewed activity on stable earthflows. However, in the absence of a forest cover, such as during the post-harvest period, and until evapotranspiration recovers sufficiently to influence soil moisture levels (~2 years), additional runoff will likely result in increased movement rates of already mobilised earthflows, and prolong their activity into periods traditionally associated with soil moisture deficit. Nonetheless, the staged harvesting of watersheds surrounding earthflows may in some instances lessen the duration of earthflow activity and associated risk of damage.

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